APPLICATIONS OF LASER SCATTERING PROBES TO TURBULENT DIFFUSION FLAMES

FINAL REPORT

Contract N00014-80-C-0882

Submitted to

Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

Prepared by
General Eiectric Company
Corporate Research and Development
Schenectady, New York 12301

November 1983

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) SRD-84-012	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION General Electric Company Corporate Research and Development 6b. OFFICE SYMBOL (*If applicable*)	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research Department of the Navy
6c. ADDRESS (*City, State and ZIP Code*) P.O. Box 8 Schenectady, NY 12301	7b. ADDRESS (*City, State and ZIP Code*) Arlington, VA 22217
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research Department of the Navy 8b. OFFICE SYMBOL (*If applicable*)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-80-C-0882
8c. ADDRESS (*City, State and ZIP Code*) Arlington, VA 22217	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT NO.
11. TITLE (*Include Security Classification*) Applications of Laser Scattering Probes to Turbulent Diffusion Flames	
12. PERSONAL AUTHOR(S) M. Lapp, M.C. Drake, C.M. Penney, and R.W. Pitz	
13a. TYPE OF REPORT Final	13b. TIME COVERED FROM 80 Sep 1 TO 83 Aug 31
14. DATE OF REPORT (*Yr., Mo., Day*) 83 Nov	15. PAGE COUNT
16. SUPPLEMENTARY NOTATION	

17. COSATI CODES			18. SUBJECT TERMS (*Continue on reverse if necessary and identify by block number*)
FIELD	GROUP	SUB. GR.	turbulent combustion, lasers, Raman

19. ABSTRACT (*Continue on reverse if necessary and identify by block number*)

The objective of this work is to determine flame properties useful for the advancement of combustion system modeling procedures and design aids, particularly in areas related to the interactions between flame turbulence properties and high temperature combustion chemistry. Toward this goal, measurements have been made of flame structure important for understanding and verifying the basic assumptions upon which the models are based. Thus, we have used spontaneous Raman scattering to determine average and excursion values of the flame front and the viscous superlayer for a co-flowing jet turbulent diffusion flame, and planar laser-induced fluorescence to provide two-dimensional instantaneous images of the flame reaction zones themselves over a range of Reynolds numbers.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL M. Keith Ellingsworth	22b. TELEPHONE NUMBER (*Include Area Code*) 22c. OFFICE SYMBOL Code 473

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

FINAL REPORT - TECHNICAL SUMMARY

This report presents a technical summary of work accomplished under the ONR sponsorship of Contract Number N00014-80-C-0882, for the period September 1, 1980 to August 31, 1983.

Abstract

The objective of this work is to determine flame properties useful for the advancement of combustion system modeling procedures and design aids, particularly in areas related to the interactions between flame turbulence properties and high temperature combustion chemistry. Toward this goal, measurements have been made of flame structure important for understanding and verifying the basic assumptions upon which the models are based. Thus, we have used spontaneous Raman scattering to determine average and excursion values of the flame front and the viscous superlayer for a co-flowing jet turbulent diffusion flame, and planar laser-induced fluorescence to provide two-dimensional instantaneous images of the flame reaction zones themselves over a range of Reynolds numbers.

Background

In developing models of combustion processes useful for the design of advanced turbine propulsion devices, mean properties are primarily of interest. Thus, average temperature or major species concentration profiles at various flame positions are examples of important desired data, and have been the focus of extensive experimental measurement programs.

However, other classes of combustion-related questions are best addressed

from experimental measurements of instantaneous flame properties. Thus, for example, continued interest exists in whether or not unique flame front structures (which may be coherent) exist in various classes of flames. The large-scale coherent structures that have been found in shear flows motivated the initiation of this part of the program, since such structures (if they were found to exist in the flames studied) might influence prominently key properties of the flame, such as the shapes of the thermodynamic property pdf's (probability density functions) and the spatial extent of the reaction zones. If the large-scale structures are found to be present, modeling procedures capable of predicting such structures have to be formulated, and analyses made to assess whether or not they are significant in combustor-related experiments.

Over the last decade, and, particularly, in the past few years, non-intrusive light scattering methods have been developed that are designed to probe gaseous systems and provide the type of mean and instantaneous data just described. Here, we have utilized (1) spontaneous vibrational Raman scattering to obtain the mean flame structure properties, and (2) two-dimensional laser induced fluorescence images of the OH radical to obtain instantaneous pictures of the flame reaction zones and, thereby, of any unique flame front structures. (The concentration of OH radicals is far larger in the reaction zones of a flame than in surrounding regions.)

The work described in the next section on the vibrational Raman scattering probe used for the mean properties involved the utilization of a technique developed (in part) through an extensive ONR Project Squid program. This program began with the initial application of vibrational Raman scattering to average temperature measurements in laminar flames, extended its scope to

include major species compositions, and then addressed the problem of measuring time-resolved thermodynamic properties of turbulent diffusion flames (as well as coupling the thermodynamic measurements to velocity flow field data from laser velocimetry).

Achievements

(1.) Mean Flame Structure Properties

Measurements of the mean flame front and viscous superlayer positions for H_2/air co-flowing jet turbulent diffusion flames have been made utilizing repetitively-obtained pulsed Raman scattering data for the flame gas thermodynamic properties. The flames have been produced on a 3.2-mm internal diameter fuel tube in a well-calibrated 15-cm-square cross section tunnel, with flat pyrex windows on all four sides. Critical flow orifices controlled the fuel flow, with the air flow induced by a servo-controlled exhaust fan. Direct measurement by hot wire anemometry showed that the air flow rms turbulence was small (~0.2%). Extensive previous data acquisition in this tunnel has led to a high confidence level for the quality of the thermodynamic information obtained from the Raman data. (See Drake et al., 1981a, 1981b, 1980, and Lapp 1980).

Two flames were studied in detail in this phase of the program. The first was of transitional character, with a Reynolds Number Re $\simeq$ 1600, as determined by the cold H_2 fuel flow. The second was a fully developed turbulent flow, with Re $\simeq$ 8500. Both flames had visible flame lengths of about 1 m, and could be observed fully through the planar tunnel windows.

The Raman probe system provided major species (N_2, H_2, O_2, and H_2O) concen-

trations from vibrational Raman Stokes signals, as well as temperatures (greater than about 800 K) from the ratio of Stokes to anti-Stokes scattering signals. Temperatures less than about 800 K lead to anti-Stokes signals for our experimental configuration and detection system that are too small for accurate measurement, so data in this range were found by computation from the total gas density, determined from the sum of the measured mole fractions of all the major species. The concentration data are accurate to roughly ± 1 mole per cent, while the temperature data are accurate to about ± 50 K. All major properties have been determined with a precision of 4%.

For each flame studied, data were obtained in the form of probability density functions (pdf's) for all properties measured, each corresponding to ensembles of 200 to 2000 data points. They were determined at a variety of downstream stations (x/d = 10, 25, 50, 100 and 150, where x = distance downstream from the fuel tube tip and d = the tip internal diameter), for a range of vertical positions (typically, at 2 mm intervals). In addition to using the data to form pdf's for the reaction variables (temperature and major species compositions), they were utilized to form the conserved scalar mixture fraction. This parameter, which is not affected by the extent of the reaction, is given by the ratio of the total hydrogen-containing mass divided by the total flame gas mass at an instant of time for any point in space, corrected by the atomic hydrogen mass introduced by ambient humidity in the co-flowing air stream. Thus, the mixture fraction at a point is not affected by the progress of chemical reaction at that point, and can be used as a "tracer" for material (H_2) introduced through the fuel tube [as opposed to material (air) introduced in the co-flowing air stream].

Use of that conserved scalar permits a unique new method for determining diffusion flame structure. This is illustrated in Fig. 1, in which the mean flame front and viscous superlayer positions are pictured for our configuration. We have used, as described in this figure, the 50% probability point of finding hydrogen atom-containing material as the barometer of the superlayer position, and the maximum probability $P(\xi_s)_{max}$ of finding a stoichiometric gas mixture (as defined by the corresponding value of mixture fraction, ξ_s).

In Fig. 2, we show the results of this measurement procedure for Re $\sim$ 8500. Here, the flame front mean position is indicated by the curve corresponding $P(\xi_s)_{max}$, while the superlayer mean position is given by the curve for $\gamma = 0.5$. Here, γ indicates the intermittency, defined as the relative probability P' that significant amounts of fuel element (turbulent fluid) are present in the measurement volume. Thus, the intermittency is given by

$$\gamma = P[(X(H_2O) + X(H_2)) > 0.10]$$

where X is the mole fraction and where the value 0.10 is a small value that accounts for ambient humidity (and the exact choice of which does not significantly affect the results). Curves for $\gamma = 0.0$ and 1.0 are also drawn. Figure 2, therefore, shows the mean flame position illustrated within the total excursion of the viscous superlayer (shaded in gray), and provides a graphic illustration of the acquisition of spatial information from pointwide data. It directly addresses questions of the type: Over what length are the flame front and superlayer positions coincident (here, up to about x/d = 40 for $P(\xi_s)_{max}$ and $\gamma = 1.0$, but with $\gamma = 0.5$ always outside $P(\xi_s)_{max}$), and how sharply do they depart thereafter?

A preliminary account of this work was given at the 1981 Project Squid Annual Meeting (Nov. 3,4, 1981, Monterey), and a more complete description will appear in the journal Experiments in Fluids (to be submitted).

(2). Two-Dimensional Images of Flame Reaction Zones

Here, we have produced two-dimensional images of the reaction zones of a wide variety of turbulent diffusion flames (Re = 660 to 8500) produced on the same fan-induced co-flowing jet burner utilized and described in the preceding section. In Fig. 3 is shown a schematic of the apparatus used to detect the reaction zones by imaging OH fluorescence induced by the pulsed dye laser source. This work has been accepted for publication by Science, and will appear in an issue early in 1984. The work was accomplished in an effort that involved collaboration under a subcontract with the Department of Mechanical Engineering of Stanford University (Ronald K. Hanson, George Kychakoff, and Robert D. Howe), who brought their image-intensified photodiode array camera to the General Electric facility and who subsequently provided substantial data acquisition and reduction.

The OH concentration data were obtained using a pulsed (7 ns duration) frequency doubled Nd:Yag-pumped dye laser source tuned to a specific OH transition (electronic-vibrational-rotational). The laser pulse was formed into a sheet using cylindrical lenses, and the resultant plane of laser light (about 40 mm wide by 400μm thick) caused OH fluorescence from the illuminated zone which was detected by the array camera. Digital images of the planar fluorescence were then stored on floppy discs.

The results from these experiments indicated that high quality images of turbulent flame reaction zones would be obtained. Inspection of the data

indicated that laminar flame reaction zone structures did not vary significantly in width and position from laser pulse to laser pulse, and that at x/d=50 the reaction zone widths (defined from the 0.1-maximum points) varied from 4.8 to 7.8 mm, with 6 mm being the most probable value.

The turbulent flame data, on the other hand showed substantial shot-to-shot variations, with a 1.2 to 9.6 mm width (and a most probable value of 2.1 mm) for x/d=50. The decrease of most probable width going from laminar to turbulent flames arises because of flame stretching from the increased shear forces. The wide range of measured widths may be introduced experimentally by (variable) non-orthogonality of the reaction sheet to the image plane, or of pairing and overlapping of different reaction zone sheets.

Turbulent reaction zone structures observed at large ($x/d \geq 100$) distances downstream showed strikingly different effects, with unattached pockets in the reaction zones (at least in the imaged plane), and with some zones that did not extend continuously across the image (possibly indicating breakup of the flame sheet).

In addition to casting light on the possibilities of large-scale structures in reacting flows, these data provide a highly matrixed form of information gathering for producing radial or axial profiles of OH radical concentration. These data, in turn, could be compared with other data for corresponding flame properties (as, for example, comparing mean flame front positions from $P(\xi_s)_{max}$, described in Part (1) of this section, with the maximum value of radial OH concentration profiles determined from the fluorescence data).

FIGURE CAPTIONS

Fig. 1 - Schematic Diagram of Mean Flame Front and Visions Superlayer Positions.

Fig. 2 - Axial Profile of the Average Position of the Flame Reaction Zone, P $(\xi_s)_{max}$, and the Viscous Superlayer, $\gamma = 0.5$, as well as the Total Excursion of the Superlayer (γ = 0.0 to 1.0).

Fig. 3 - Schematic of Experimental Configuration for Planar Laser-Induced OH Fluorescence Imaging of Flame Fronts.

PUBLICATIONS

The following is a listing of publications supported in part by ONR that detail the research results described here.

M. C. Drake, M. Lapp, C. M. Penney, S. Warshaw, and B. W. Gerhold, "Measurements of Temperature and Concentration Fluctuations in Turbulent Diffusion Flames Using Pulsed Raman Spectroscopy," Eighteenth Symp. (Int.) on Combustion, The Combustion Institute, 1981, p. 1521.

M. C. Drake, M. Lapp, C. M. Penney, S. Warshaw, and B. W. Gerhold, AIAA Paper No. 81-0103, 1981.

M. Drake, M. Lapp, C. M. Penney, and S. Warshaw, "Characterization of Turbulent Flames by Single-Pulse Raman Measurements," in Proceedings of the 7th International Conference on Raman Spectroscopy, W. F. Murphy, Ed., North-Holland Publishing Co., Amsterdam, 1980, p. 230.

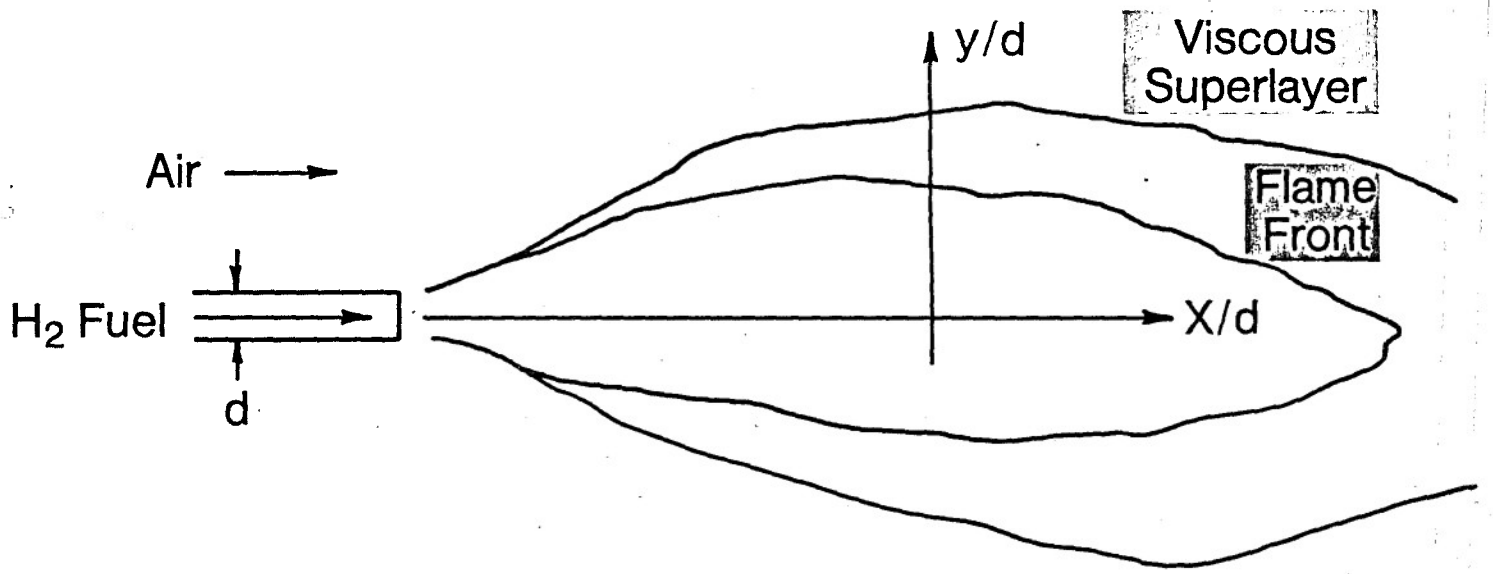
M. Lapp, "Raman Scattering Measurements of Combustion Properties," in Laser Probes for Combustion Chemistry, American Chemical Society Symposium Series, Vol. 134, D. R. Crosley, Ed., American Chemical Society, Washington, D. C., 1980, Chapt. 17.

M. C. Drake, M. Lapp, C. M. Penney and R. W. Pitz, "The Structure of Turbulent Jet Diffusion Flames From Raman Scattering and Schlieren Data," to be submitted to Experiments in Fluids.

G. Kychakoff, R. D. Howe, R. K. Hanson, M. C. Drake, R. W. Pitz, M. Lapp, and C. M. Penney, "The Visualization of Turbulent Flame Fronts Using Planar Laser-Induced Fluorescence," accepted in Science.

FLAME STRUCTURE FROM RAMAN DATA

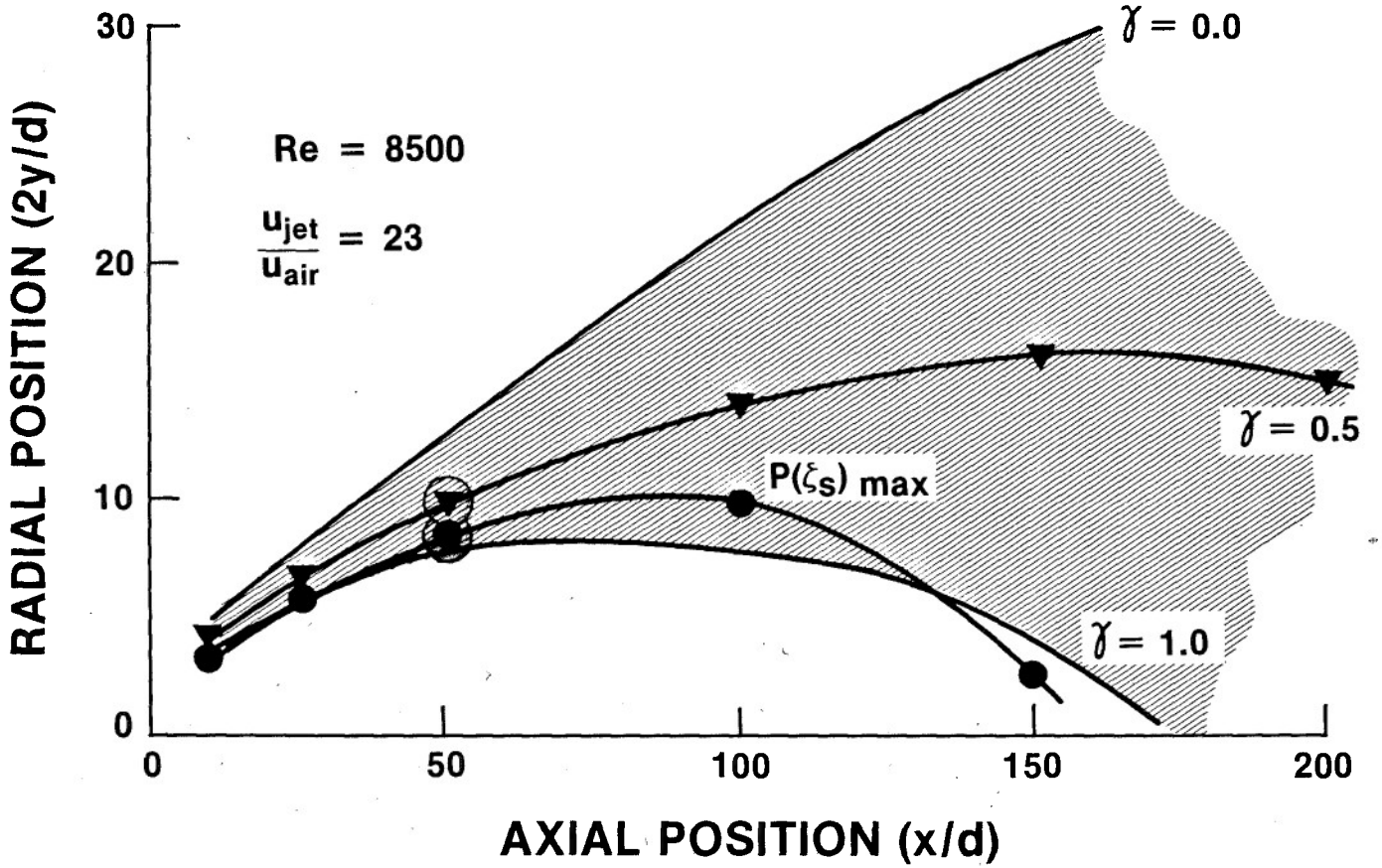
TURBULENT CO-FLOWING JET DIFFUSION FLAME COMBUSTOR:

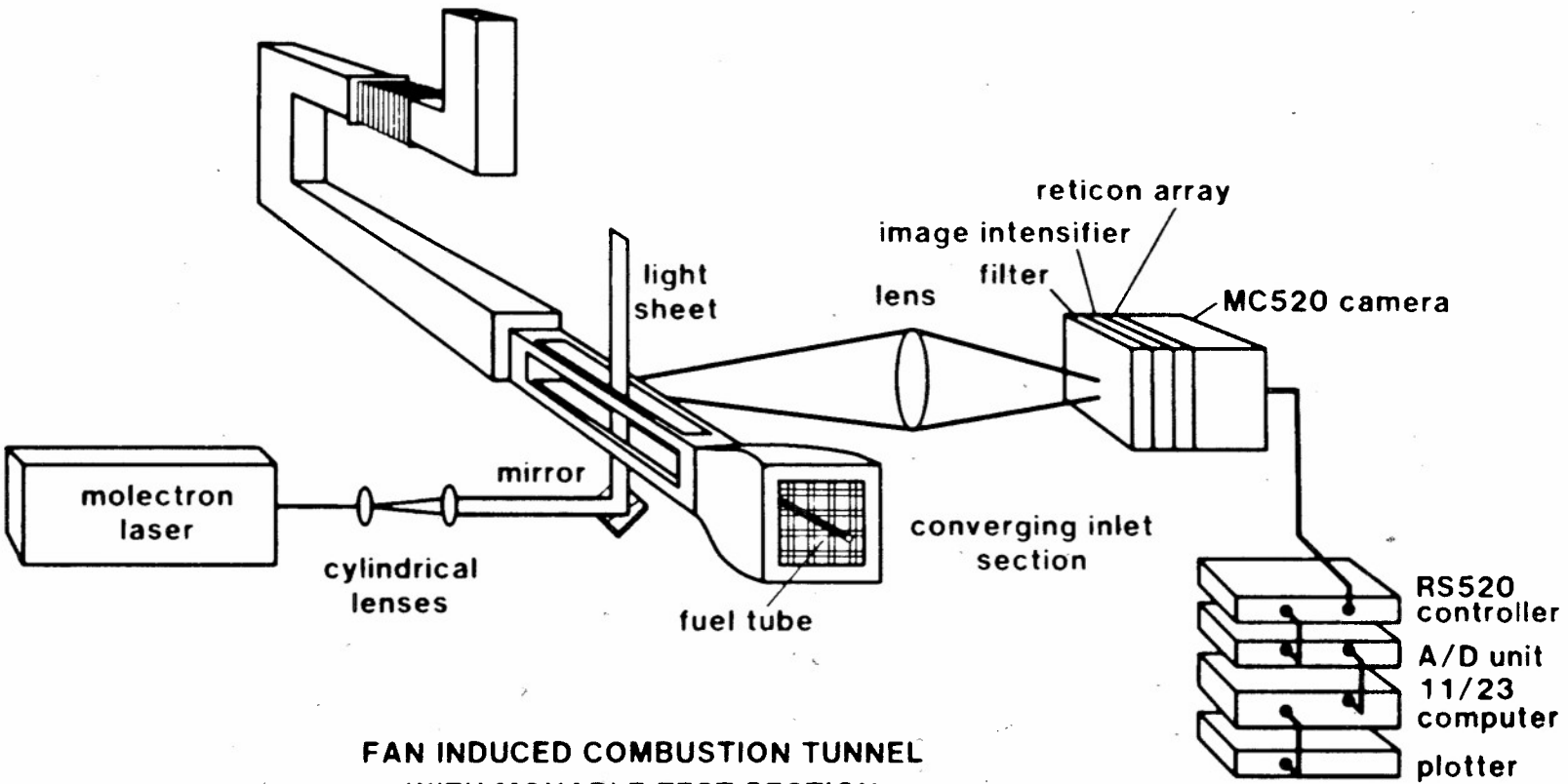


Use Fuel Species to Determine Structure:

- Let 50% Probability of Finding "Significant" Amount of H-Atom Species (H_2 + H_2O)Define Superlayer— Conserved Scalar Concept
- Let Maximum Probability of Finding Stoichiometric H_2/Air Mixture Define Flame Front

AXIAL PROFILES OF: AVERAGE FLAME FRONT POSITION [$P(\zeta_s)_{max}$]
AVERAGE SUPERLAYER POSITION [$\gamma = 0.5$]
EXCURSION OF SUPERLAYER [$\gamma = 0.0$ TO 1.0]





FAN INDUCED COMBUSTION TUNNEL
WITH MOVABLE TEST SECTION